Semiconductor sensors

- Semiconductors widely used for charged particle and photon detection
  - based on ionisation - same principles for all types of radiation

- What determines choice of material for sensor?
  - Silicon and III-V materials widely used
    - physical properties
    - availability
    - ease of use
    - cost

- silicon technology is very mature
  - high quality crystal material
  - relatively low cost
  - but physical properties do not permit it to be used for all applications

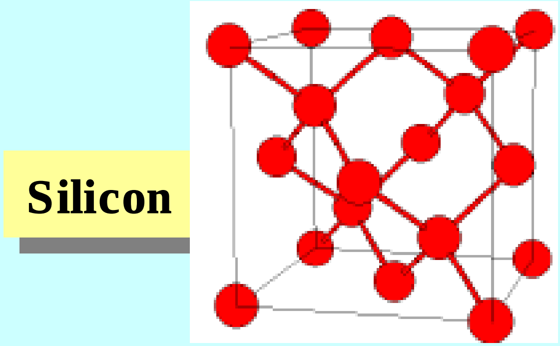
Semiconductor fundamentals reminder

•Crystalline

lattice symmetry is essential

atomic shells => electron energy bands

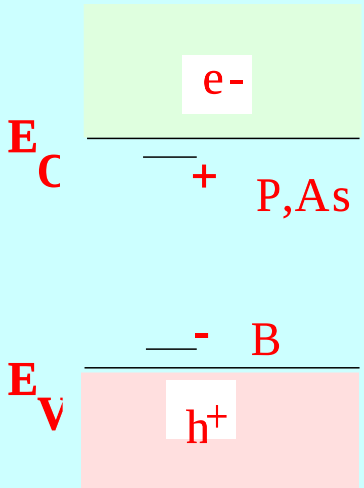
energy gap between valence and conduction bands



•Dope material with nearby valence atoms

donor atoms => n-type *excess mobile electrons*

acceptor atoms => p-type *holes*



•Dopants provide shallow doping levels

normally ionised at ~300K

conduction band occupied at room temp
NB strong T dependence

•Two basic devices

p-n diode

MOS capacitor

basis of most sensors and transistors

p-n diode operation

•imagine doped regions brought into contact

•establish region with no mobile carriers

built-in voltage

electric field

maximum near junction

•forward bias

overcome built-in voltage

current conduction

$$I \sim I_0[\exp(qV/kT) - 1]$$

•increase external reverse bias

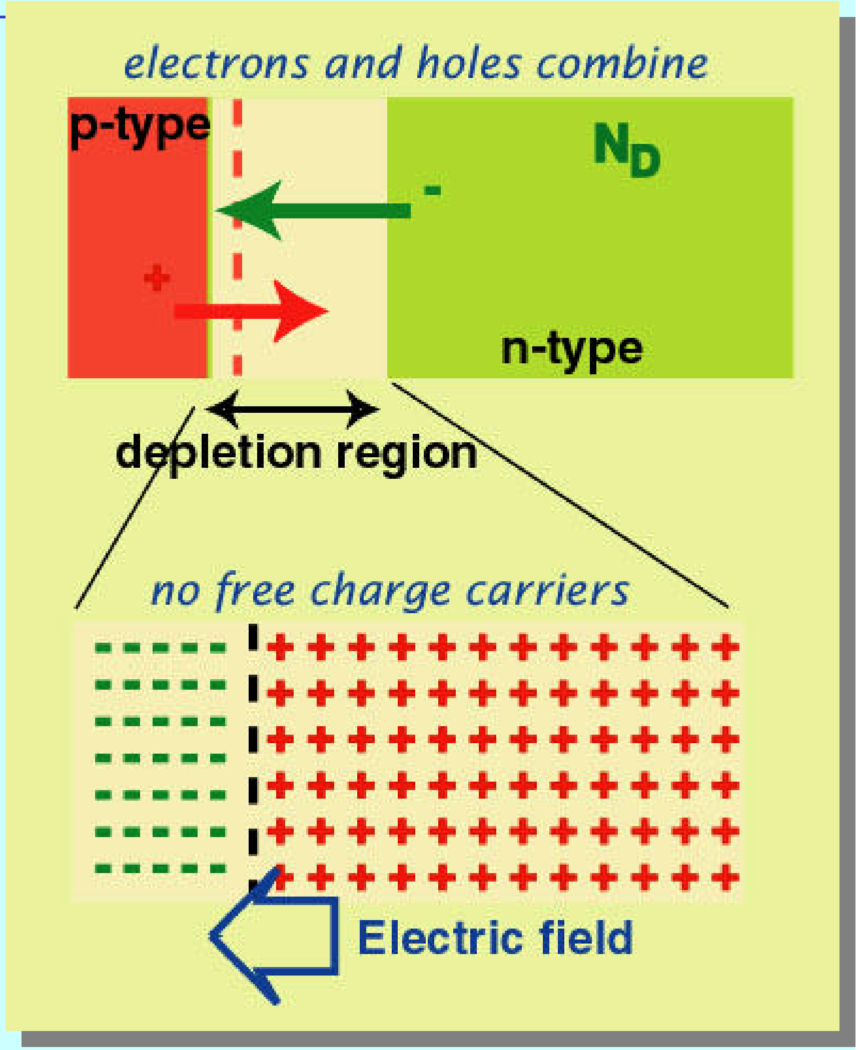
increase field

increase depletion region size

reduce capacitance ≈ εA/d

small current flow

sensor operation



Requirements on diodes for sensors

•Operate with reverse bias

should be able to sustain reasonable voltage

larger E (V) = shorter charge collection time

•Dark (leakage) current should be low

noise source

ohmic current = power

•Capacitance should be small

noise from amplification ~ C

defined by geometry, permittivity and thickness

circuit response time ~ [R] x C

•Photodetection

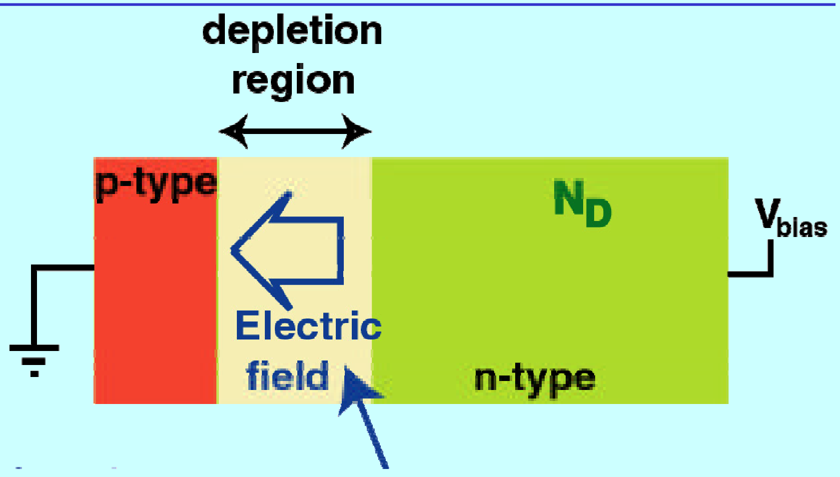
thin detector: high E but high C unless small area

•X-ray and charged particle detection

"thick" detectors required for many applications

efficiency for x-rays

larger signals for energetic charged particles



dielectric between conducting regions

commercial packaged photodiodes

Diode types

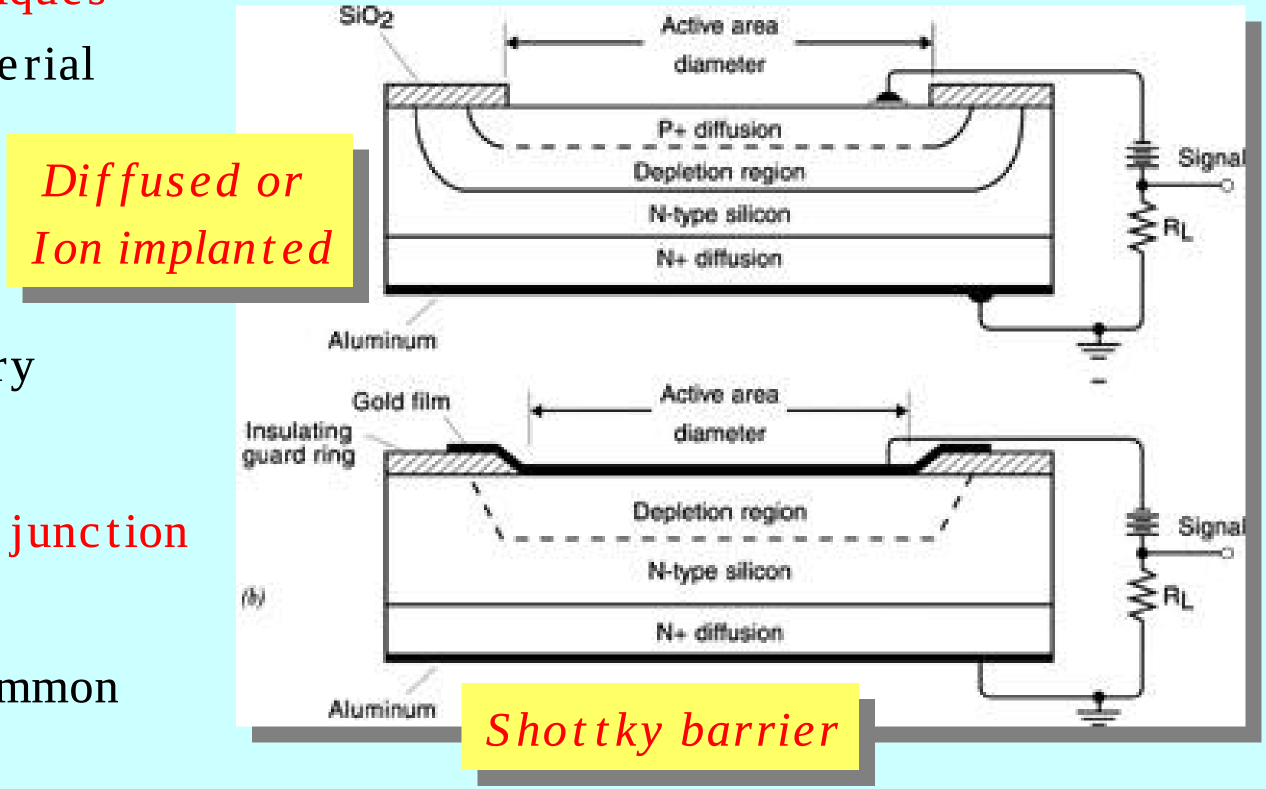
•Variety of manufacturing techniques

depends on application & material

•Diffused & Ion implanted

oxide window

robust, flexible geometry



•Shottky barrier - metal-silicon junction

thin metal contact

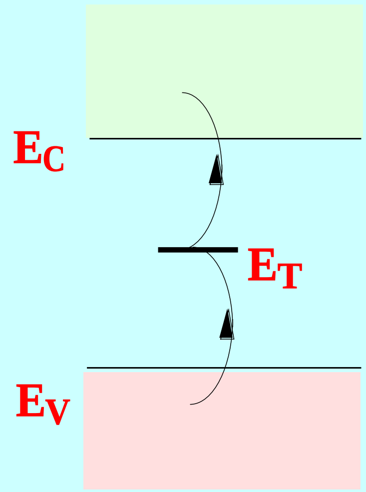
more fragile and less common

•III-V

epitaxial = material grown layer by layer

limits size, but essential for some modern applications

Real p-n diode under reverse bias



- Dark (leakage) current

  electrons & holes cross band-gap

  diffusion from undepleted region

  thermal generation--recombination

- Magnitude depends on...

  temperature (and energy gap) ~ $\exp(-\alpha E_{gap}/kT)$

  position of levels in band gap

  density of traps

  ease of emission and capture to bands

  availability of carriers & empty states

- Mid-gap states are worst

  avoid certain materials in processing

  structural defects may arise in crystal growth

Sensor materials

Property	Si	Ge	GaAs	SiO_2
Z	14	32	31/33	
Band gap [eV]	1.12	0.66	1.42	9
Energy to create e-h pair [eV]	3.55	2.85	4.1	17
Density [g.cm^{-3}]	2.33	5.33	5.32	2.2
Permittivity [pF/cm]	1.05	1.42	1.16	0.35
Electron mobility [cm^{2}.V^{-1}.s^{-1}]	1450	3900	8500	~20
Hole mobility [cm^{2}.V^{-1}.s^{-1}]	450	1900	400	10^{-4}-10^{-6}
Intrinsic resistivity [Ω.cm]	2.3 10^{5}	47	10^{8}	
Average MIP signal [e/µm]	110	260	173	20
Average MIP dE/dx [MeV/g.cm^{-2}]	1.66	1.40	1.45	1.72

MIP = minimum ionising particle

•mobility $\underline{v} = \mu \underline{E}$

mobilities for linear region. At high E v saturates: ~ 10^{5} m.s^{-1}

Silicon as a particle detector

- Signal sizes

  typical H.E. particle ~ 25000 e 300µm Si

  10keV x-ray photon ~ 2800e

- no in-built amplification

  E < field for impact ionisation

- Voltage required to deplete entire wafer thickness

Ge	large crystals possible higher Z must cool for low noise
GaAs	less good material - electronic grade crystals less good charge collection

$V_{depletion} \approx (q/2\varepsilon)N_D d^2$ N_D = substrate doping concentration

$N_D \approx 10^{12}$ cm^{-3} => $\rho = (q\mu N_D)^{-1} \approx 4.5$kΩ.cm

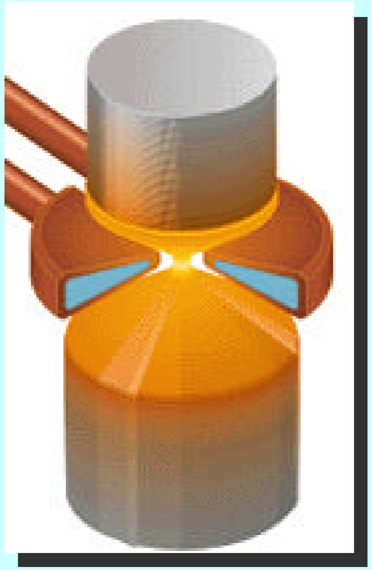
$V_{depletion} \approx 70$V for 300µm

- electronic grade silicon $N_D > 10^{15}$ cm^{-3}

  $N_D = 10^{12} : N_{Si} \sim 1 : 10^{13}$ *ultra high purity !*

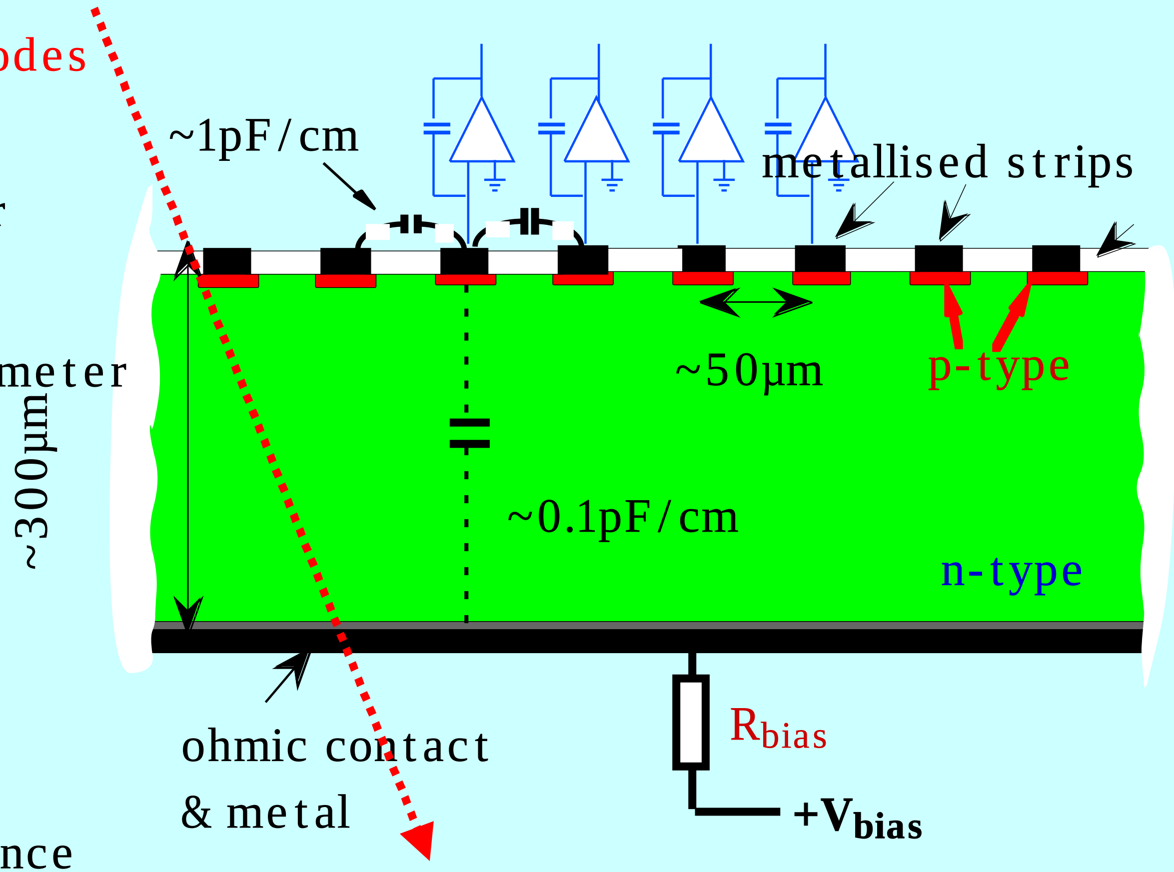
  further refining required

  Float Zone method: local crystal melting with RF heating coil



Silicon microstrip detectors

- Segment p-junction into narrow diodes
  - E field orthogonal to surface
  - each strip independent detector
- Detector size
  - limited by wafer size < 15cm diameter
- Signal speed
  - $\langle E \rangle \geq 100V/300\mu m$
  - p-type strips collect holes
  - $v_{hole} \approx 15\ \mu m/ns$
- Connect amplifier to each strip
  - can also use inter-strip capacitance
  - & reduce number of amplifiers to share charge over strips
- Spatial measurement precision
  - defined by strip dimensions and readout method
  - ultimately limited by charge diffusion $\sigma \sim 5\text{-}10\mu m$



Applications of silicon diodes

- Microstrips heavily used in particle physics experiments

    excellent spatial resolution

    high efficiency

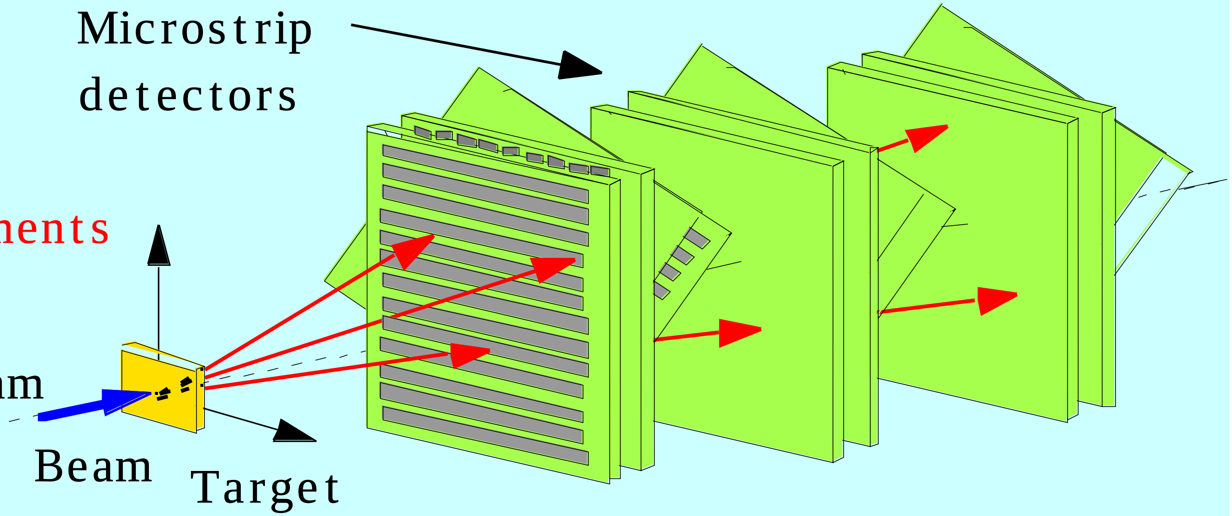
    robust & affordable

    magnetic effects small

- Telescopes in fixed target experiments

    - or satellites

    cylindrical layers in colliding beam



- x-ray detection

    segmented arrays for synchrotron radiation

    pixellated sensors beginning to be used

- Photodiodes for scintillation light detection

    cheap, robust, compact size, insensitive to magnetic field

Photodetection in semiconductors

- For maximum sensitivity require

    minimal inactive layer

    short photo-absorption length

        strongly λ and material dependent

- Silicon ($E_{gap} \approx 1.1eV$)

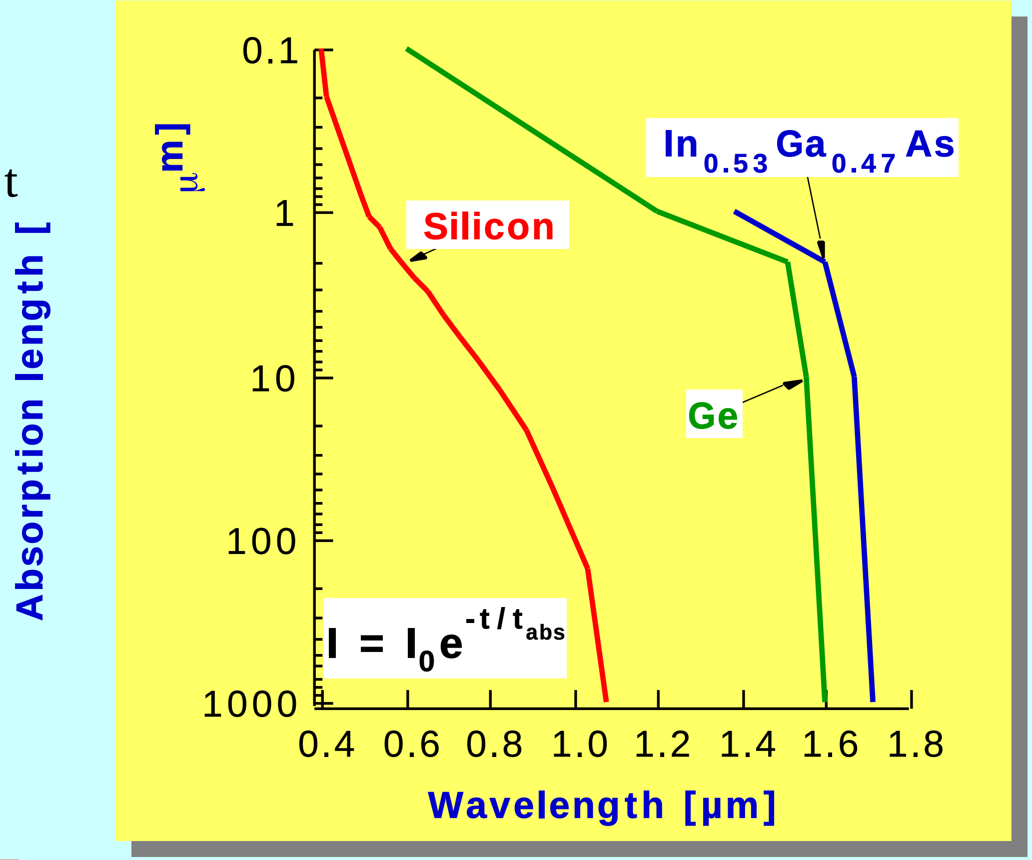
    infra-red to x-ray wavelengths

    other materials required for $\lambda > 1\mu m$

- III-V materials

    GaAs, InP $\lambda < 0.9\mu m$

    GaP $\lambda < 0.6\mu m$



- Engineered III-V materials, Ge - larger E_{gap}

    telecommunications optical links at 1.3μm & 1.55μm

    + short distance optical links ~0.85μm

Photodiode spectral response

- Units QE (η) or Responsivity (A/W)

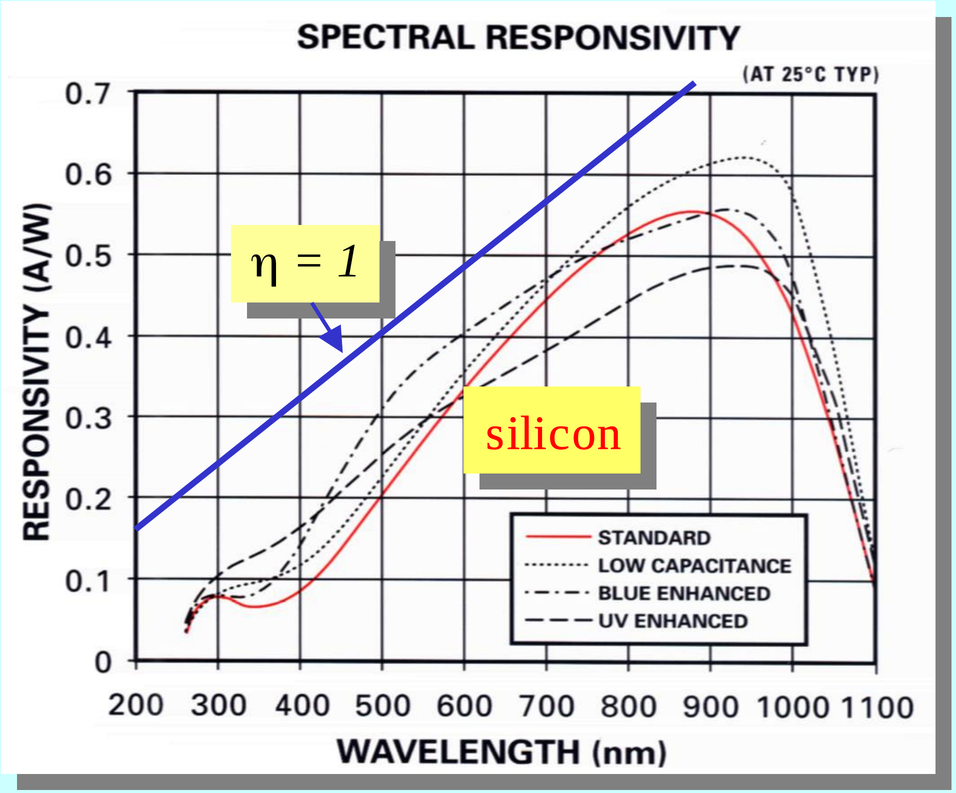
$P = N_\gamma . E_\gamma / \Delta t$

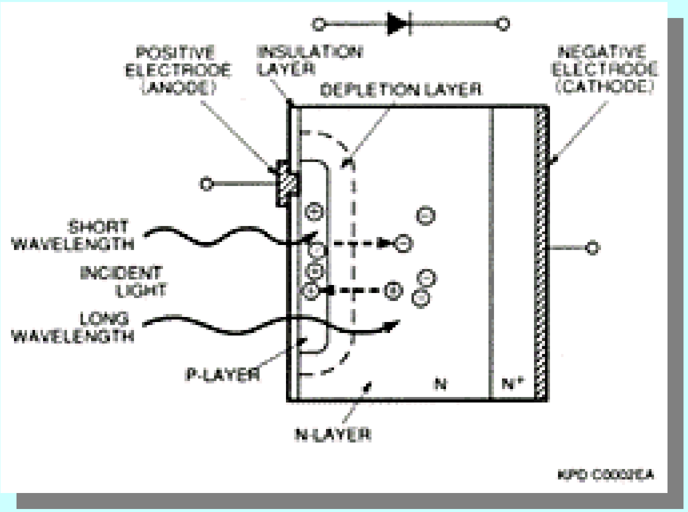
$I = \eta . N_\gamma . q_e / \Delta t$

$R = \eta . q_e . \lambda / hc \approx 0.8 \, \eta \, \lambda[\mu m]$

- silicon QE ~ 100% over broad spectral range

- windows and surface layers also absorb





Heterojunction photodiodes

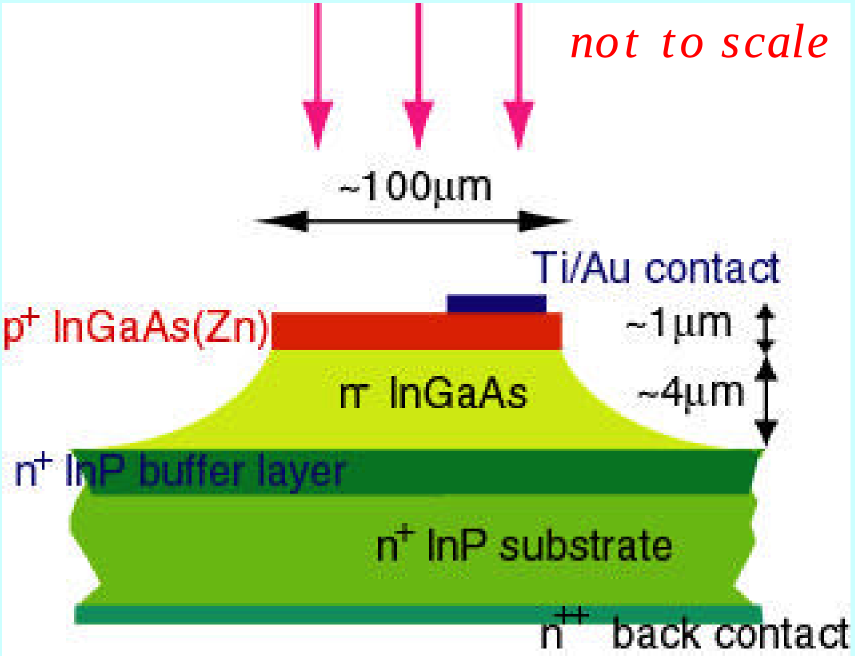
•For infra-red wavelengths, special materials developed

•drawbacks of p-n structure

thin, heavily doped surface layer

carrier recombination

=> *lower quantum efficiency*



•heterojunction

wider band gap in surface layer

minimise absorption

most absorption in sub-surface

narrower band-gap material

higher electric field

illumination through InP substrate also possible for long λ

mesa etching minimises area

Avalanche photodiodes

•p-n diode

Electric field is maximum at junction

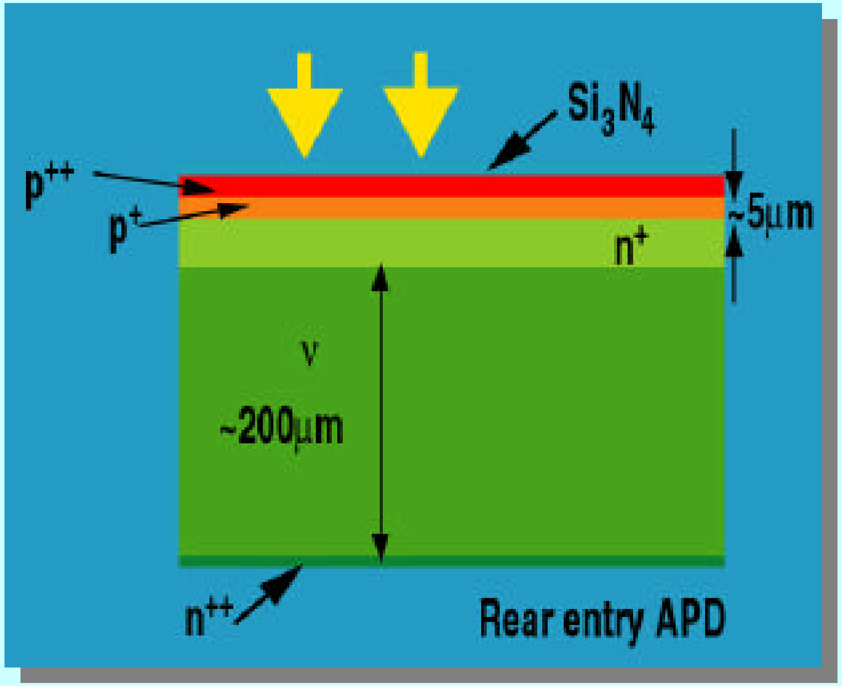
but below threshold for impact ionisation

$E_{max} \approx 2V/d \sim kV/cm$

•APD *tailor field profile by doping*

Detailed design depends on λ (*i.e. absorption*)

much higher E fields possible



•Pro

gain - valuable for small signals

fast response because high E field

•Con

Risk of instability

amplify dark current & noise

edge effects - breakdown in high field regions

APD characteristics

- This (example) design optimised for short wavelength

  λ ~ 400nm   *short absorption length*

  for infra-ref wavelengths *-longer absorption length*

  so entry from ohmic contact surface to maximise absorption